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HEAVY ION COLLISIONS

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Abstract

Heavy ion collisions at ultra-relativistic energies offer the unique possibility to study strongly interacting matter under extreme conditions of temperature and density and to search for the conjectured quark-gluon-plasma. The first phase of experiments with relatively light ions is now completed and a new round of much heavier ions has started with 10 GeV/u Au beams at BNL and 160 GeV/u Pb beams at CERN. A general overview of the present experimental status is given emphasizing those results which clearly show that heavy ion collisions cannot be interpreted as a mere superposition of independent nucleon-nucleon collisions.

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1 INTRODUCTION

The main goal of ultra-relativistic heavy ion physics is the study of hadronic matter under extreme conditions of density and temperature and in particular to search for evidence of the phase transition(s) [1] leading to Quark Gluon Plasma (QGP) formation –where quarks and gluons are free to move over a large volume compared to the typical size of hadrons– and to chiral symmetry restoration where masses drop to zero. Figure 1 shows a schematic phase diagram of the transition from hadronic to quark matter; the necessary conditions of temperature and density are indicated in the figure, together with the possible paths followed in ultra-relativistic heavy ion collisions. At high temperature and low density, the conditions are those which presumably prevailed in the universe a few microseconds after the big bang, whereas at the other extreme of low temperature and high density the conditions may be close to those inside neutron stars. This phase transition is predicted by lattice QCD calculations although it is still unclear whether the transition is of first or second order type [2]. The phase transition which restores chiral symmetry is also predicted to occur under very similar conditions.

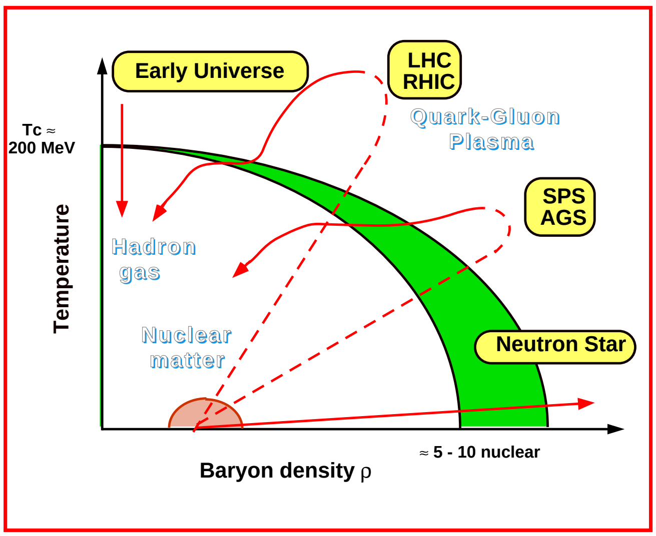

Figure 1: Phase diagram of hadronic matter

The possibility to create in the laboratory this new state of matter has aroused great interest. An impressive experimental effort started almost simultaneously at the AGS of BNL and at the SPS of CERN nearly ten years ago with relatively light ions, O and Si of 14 GeV/u at BNL and O and S ions of up to 200 GeV/u at CERN. This light ion phase is now completed and has provided a wealth of very interesting results [3]; prominent among them are the early results which clearly demonstrated that it is possible to handle experimentally the very high multiplicity events and that a high density state of matter is produced with energy densities comparable to those predicted for the phase transition to occur. A new round of experiments, with really heavy ions, has started in 1992 with Au ions of 10 GeV/u at the AGS and a year ago with Pb ions of 160 GeV/u at CERN. The advantages are a considerable increase in the volume of the system together with slightly larger energy density. Furthermore the unprecedented large multiplicities attainable in central Pb-Pb collisions (~500 charged particles per unit of rapidity) open the unique possibility to perform a physics analysis on an event-by-event basis. This second round is expected to continue for a few more years.

The success of the present program would have not been possible without the continuous development of new experimental tools to meet the challenges of very high multiplicity events, and in particular to track and identify copiously as well as scarcely produced particles. I will quote here only a few of these tools, multi-layer silicon pixel detectors [4], silicon radial-drift chambers [5], hadron-blind RICH detectors [6] and large volume TPC's [7].

The experiments cover a very broad spectrum of observables which can be divided in two categories: (i) global (like the transverse energy E_t and charged particle distributions) and hadronic observables (p_t distributions, particle production cross sections, two-particle correlations); they provide crucial information about the reaction dynamics and in particular about the energy density achieved, and the size and properties of the final hadronic system at freeze-out i.e. when the hadrons cease to interact. (ii) observables which have been proposed as signatures for the phase transition; the most prominent ones for QGP formation are dileptons, direct photons, J/ψ suppression, and strangeness enhancement. The ρ meson, with its very short lifetime is considered one of the best probes of the chiral symmetry restoration.

It is not possible in the limited space of this review to do justice to the vast amount of data available and a selection is unavoidable. I will first give in Section 2 an overview of the the main results from global and hadronic observables. I emphasize the first results which have already emerged from the Pb beam at CERN but otherwise most of the section is devoted to the light ion phase. (For a more detailed account on these observables see the recent report by R. Stock [8]). I will then focus for the rest of this review on specific signatures. In Section 3, I present in some detail the recent results on enhanced production of lepton pairs ($e^+e^-, \mu^+\mu^-$) which have fueled a great theoretical interest. The present status of the search for direct photons and of charmonium suppression is summarized in Sections 4 and 5 respectively. Section 6 gives a short summary together with the perspectives for the immediate and more distant future.

2 GLOBAL AND HADRONIC OBSERVABLES

E_t and energy density in Pb-Pb collisions

One of the major landmarks of last year was the availability of the 160 GeV/u Pb beam at the CERN SPS. Figure 2 shows one of the first results [9]; the transverse energy distribution as measured by the NA49 experiment in Pb-Pb collisions at around mid-rapidity is compared with the older results obtained in S-Au collisions. An increase by a factor of three in the maximum transverse energy is observed. In both cases the shape is entirely governed by the geometry of the collision; a plateau corresponding to a large range of impact parameters where the two nuclei overlap, rapidly falling when reaching central collisions at b=0. The data are very well reproduced by calculations based on the VENUS model [10] which includes secondary interactions of the produced particles whereas the FRITIOF code [11] which does not include them, fails to reproduce the large E_t region.

We now turn to one of the key questions, namely do these collisions produce a system

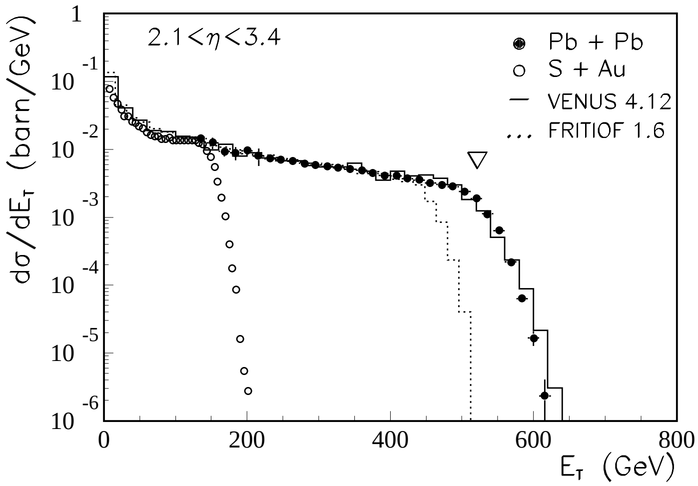

Figure 2: Transverse energy distribution of Pb-Pb at 160 GeV/A and S-Au at 200 GeV/A compared to calculations using the FRITIOF and VENUS event generators [9]

Table 1: Energy densities achieved at the SPS [9].

System	E_{lab}/A (GeV)	ϵ (GeV/fm^3)
S+Au	200	2.6
Pb+Pb	158	3.2

of high enough energy density for a phase transition to occur? Already the first results obtained with O and S ions at the SPS indicated a positive answer [12] and the recent Pb results confirm it. The energy density is inferred from the energy deposited in the system –reflected in the measured transverse energy or alternatively in the number of produced particles– together with a model for the initial interaction volume. The most widely used prescription is the one proposed by Bjorken [13]. In his scenario of boost invariant expansion, the energy density ϵ is proportional to the transverse energy density in rapidity space dE_t/dy:

$$\epsilon = \frac{1}{\pi R^2 \tau} \frac{dE_t}{dy}$$

where R is the projectile radius (R=1.12A$^{1/3}$), and τ is the formation time which is usually assumed to be 1 fm/c. The energy densities achieved with the S and Pb beams at SPS energies are shown in Table 1. They are similar. This results from the fact that the larger transverse energy rapidity density, (which increases, like the maximum E_t, by a factor of three from S to Pb) is practically compensated by the volume increase, resulting in a moderate gain of only ~20% in energy density. As mentioned earlier, the real advantage of the Pb beam is the increase in the size of the system. The important point to notice here is that the achieved densities are very high –∼20 times larger than in normal nuclear matter ($\sim 0.16 GeV/fm^3$) and ∼7 times larger than inside a nucleon– and within the range of values predicted for the deconfinement phase transition to occur.

Equilibrium and Strangeness

Another crucial question is whether or not the system reaches thermal and chemical equilibrium to justify the use of statistical QCD and thermodynamics as the appropriate theoretical framework to describe these collisions. A necessary prerequisite in the path towards thermalisation is sufficient rescattering of the incident as well as the produced particles; density, size and lifetime are therefore the important parameters here. We already saw in the previous section (see Figure 2) that the comparison of the measured E_t distributions with event generators (with and without rescattering) clearly indicates that a considerable amount of rescattering indeed takes place. Two-particle correlations also support the same conclusion.

The most direct way to test the thermal hypothesis is to study in detail the particle abundances over the whole phase space. If we assume that an ideal hadron gas in equilibrium is formed, then all particle production ratios are governed by only two independent variables, the temperature T and the baryochemical potential μ_B characterizing the system at freeze-out [14]. Enough data have been accumulated over the last years to address this issue in a systematic manner. An analysis of many ratios obtained in the light ion phase has recently been performed. It strongly supports the claim that both thermal and chemical equilibrium are reached at AGS and SPS energies [15] yielding freeze-out temperatures of ∼130 and ∼160 MeV and baryon chemical potentials of 138 and 109 MeV, respectively. Newer data with the Au and Pb beams should allow to consolidate this claim as the volume and the lifetime of the system increase thereby increasing the chances to reach equilibrium. This is illustrated in Fig. 3 which shows the increase of the K^+/π^+ ratio measured at the AGS [16] as a function of the nuclear size from p-p up to Au-Au collisions where the ratio reaches the thermal limit for a system at T∼150 MeV. The agreement with the thermal analysis is remarkable keeping in mind

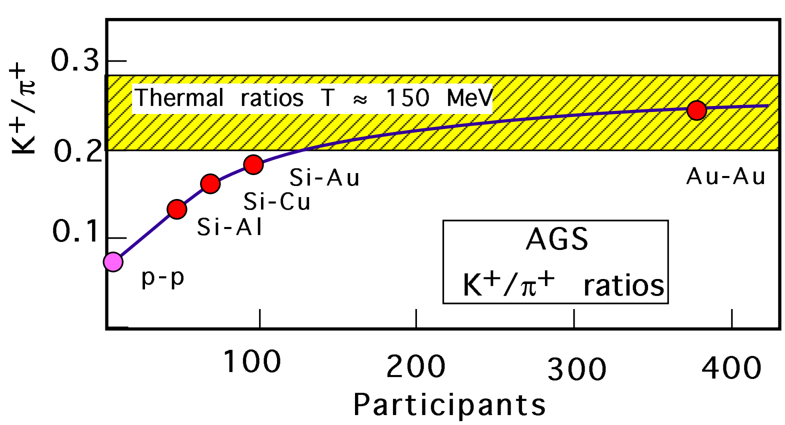

Figure 3: K^+/π^+ ratio measured at the AGS [16]

that it has some caveats; in particular one could question the assumption of a common

Table 2: Strange and Multistrange baryon production in S-W at the SPS [19] compared to thermal model predictions [15].

Particles	Measured ratio y=2.3 - 3.0	Thermal model T = 160 MeV
$\overline{\Lambda}/\Lambda$	0.20±0.01	0.20
Ξ^-/Λ	0.095 ±0.006	0.12
$\Xi^+/\overline{\Lambda}$	0.21 ±0.02	0.20
Ξ^-/Ξ^+	0.45 ±0.05	0.31
$\frac{(\Omega^+ + \Omega^-)}{(\Xi^+ + \Xi^-)}$	0.8±0.4	0.17

freeze-out temperature for all particle species. Since particle emission is expected to occur when the mfp is comparable to the size of the system, different particles could decouple at different times i.e. at different temperatures.

It is interesting to consider the results of the thermal analysis in the context of strangeness production. Strangeness enhancement was one of the first proposed signatures for QGP formation [17]. It results from a decrease of the strange quark mass in the plasma from ~500 MeV to ~ 150 MeV, and from the large chemical potential for u and d quarks due to the large number of valence quarks, favoring the formation of $s\overline{s}$ pairs. And indeed there is no doubt that the production of strange particles is enhanced both at the AGS and SPS as compared to p-p collisions [18]. The WA85 experiment for example has an impressive set of results on the production of strange and multistrange baryons (Λ, Ξ and Ω)in S-W and S-S collisions [19], which are presently been extended with the Pb beam. The interpretation is however far from being clear. The thermal analysis previously discussed reproduces most of these results within a factor of two. As an example, Table 2 compares the results from the WA85 experiment with those obtained from a systematic thermal analyis of the SPS S data [15]. Consequntly, it may appear that there is no need to invoke QGP formation to explain them. However, one has to keep in mind that the thermal analysis provides only a snap-shot of the system at freeze-out and it does not tell us how the system got there. We also note that strangeness saturation is reached much faster in a QGP than in a hadron gas and that the production of multistrange baryons (which is difficult in hadronic interactions, in particular the Ω) is underestimated in the thermal analysis. Therefore there could be something more beyond thermalization of a hadron gas in the strangeness signal.

Expansion and Collective Effects

Having shown that a high density state close to thermal and chemical equilibrium may indeed be formed, the next question is whether there is any indication of collective effects, like expansion or flow. Information on this topic is derived from the transverse mass $m_t = (m^2 + p_t^2)^{1/2}$ distribution of various particles and from two-particle correlations which will be discussed in the next section.

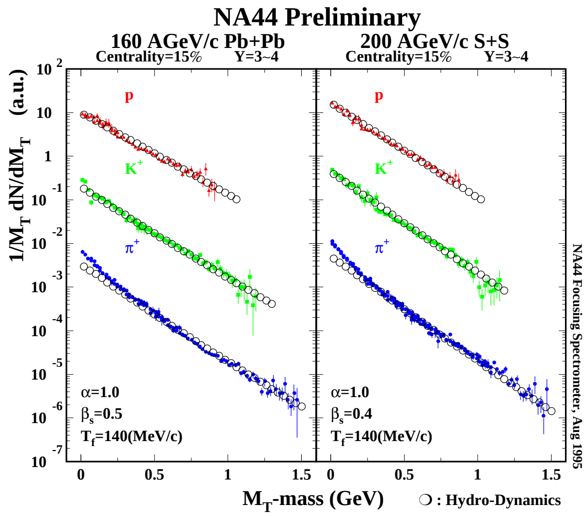

Figure 4: Transverse mass spectra of pions, kaons and protons measured by NA44 in Pb-Pb and S-S collisions.

We first point out that the m$_t$ distributions measured in p-p and p-A collisions are fairly well described by a Boltzmann distribution $1/m_t dN/dm_t = m_t e^{-m_t/T}$ with a common inverse slope or "temperature" T for all particles. This seemingly thermal behaviour is not understood at least not in p-p collisions since there is hardly any rescattering in these collisions. This result is nevertheless used as the basis for comparison to heavy-ion data. In this case, the situation is quite different. The m$_t$ distributions can still be described by a Boltzmann function, however the slope parameter increases with the particle mass. This is shown in Figure 4 which displays the m$_t$ distributions of π^+, K^+ and p measured by the NA44 experiment in S+S and Pb+Pb collisions at the SPS. The slope parameter increases also with the size of the system. The systematics are illustrated

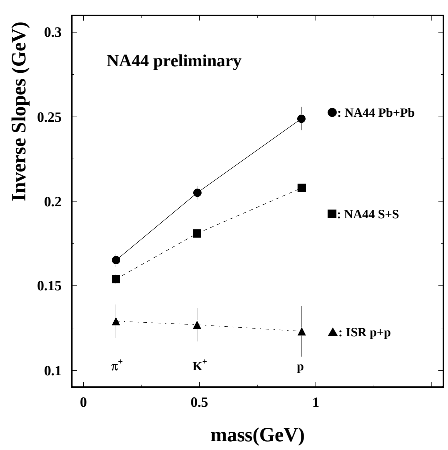

Figure 5: Inverse slopes from transverse mass distributions

in Figure 5. Similar results exist also from AGS data. In all cases, these "temperatures" exceed by far the Hagedorn limit, the maximum temperature of a thermalized hadron gas [20]. This contradiction is resolved if one postulates that there is collective radial flow [21]. The m_t distribution is then the sum of two terms– the normal thermal chaotic contribution plus the ordered radial one–. This sum results in a shape that can still be reasonably well described by a single exponential distribution, yielding the high "temperature" values quoted above. The radial velocity provides also a natural explanation for the variation of the inverse slope with mass. With such an analysis the NA44 S+S and Pb+Pb data are nicely described, by a "true" temperature of 140 MeV and an average radial flow velocity of $<\beta> = 0.4$ and 0.5 respectively. The results of the hydrodynamical fit are also shown in Figure 4. A similar analysis of AGS data (14.6 GeV/u Si+Au) yields values of T = 140 MeV and $<\beta> = 0.39$ [15]. Additional and independent evidence of flow effects at the AGS was recently provided by an analyis of the E_t azimuthal distributions in Au-Au collisions [22].

Two-Particle Correlations

Two-particle correlation is a useful tool to learn about the lifetime and size of the particle source. The procedure is very similar to the one originally developed by Hanbury-Brown and Twiss [23] to measure the radius of stars and later adapted to particle physics. The technique is widely used in ion experiments at the AGS and the SPS and as an example of the state-of-the-art data, Fig. 6 shows the correlation function of pions and kaons measured in S-Pb collisions at the SPS by the NA44 experiment. Since pions and kaons are emitted rather late, these correlations provide information about the space-time extent of the hadron system in the later stages of the collisions. The figure shows the results of a two-parameter fit (the radius R and the correlation strength λ) i.e assuming a spherical source. The interpretation of the fit parameters, in particular the relation

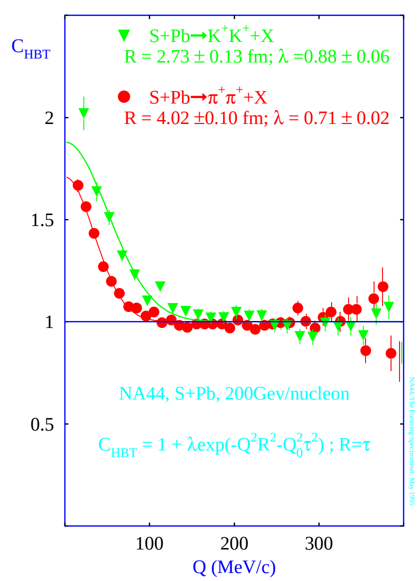

Figure 6: Pion and kaon correlation functions(NA44)

between the radius and the source size, is not straightforward [24]. In Fig. 6, for example, one sees that the pions have a larger radius than the kaons whereas their λ parameter is smaller. This could signal that kaons are emitted earlier (and therefore at a higher temperature) than pions or could result from the effect of long-lived resonance decays. The picture is complicated further by geometrical acceptance and collision dynamics effects. The help of a model is therefore needed to guide the interpretation. Several experiments are using the RQMD event generator [25], which incorporates the collision dynamics, particle production, rescattering, resonance decay etc., for that purpose. In spite of this complication, HBT remains a very useful tool as we will briefly show now. The systematic variations of the fit parameters from the AGS to the SPS and for different systems is shown in Figure 7. One sees that the increase of the radius from kaons to pions is a general result. The radius increases also with the size of the system and this trend is confirmed by preliminary results from Pb-Pb collisions. For all heavy ion projectiles, the fitted radii are larger than the projectile radius suggesting that expansion took place during the collision. A stronger support of this claim comes from the observed $1/\sqrt{m_t}$ dependence of the R parameter as predicted by a simple model of a cylindrically symmetric expanding source [26, 8]. These results point out to a thermalized expanding source thereby corroborating the picture discussed in the previous section.

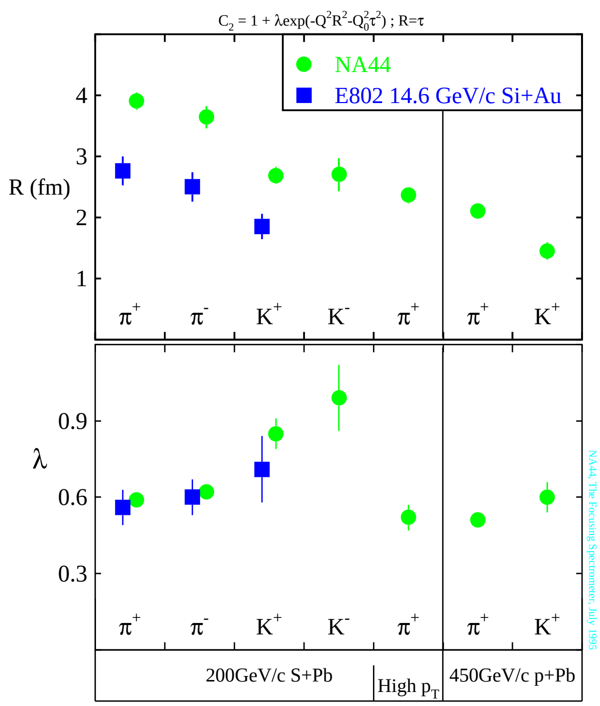

Figure 7: Systematics of HBT radius parameters

3 DILEPTONS

<u>The motivation</u>

The measurement of dileptons has always been emphasized as one of the most relevant probes to study the dynamics of relativistic heavy-ion collisions. The argument is simple and was first proposed by Shuryak more than fifteen years ago [27]: since dileptons interact only electromagnetically, their mean free path is large compared to the size of the system formed in these collisions; therefore, once produced, they can leave the interaction region and reach the detectors without any further interaction, carrying information about the conditions and properties of the matter at the time of their production. Dileptons can be emitted throughout the entire lifetime of the collision, from the hot early stages up to long after the freeze-out time when the hadrons cease to interact. However, since the emission rate is a strongly increasing function of the temperature they are most abundantly produced at the early stages when the temperature and the energy density have their largest values, thus making them a potential signature of QGP formation.

The main topic of interest is the identification of the thermal radiation emitted once the system reaches thermal equilibrium, during the expansion and cooling phases up to freeze-out. The thermal radiation could tell us about the nature of the matter formed, the conjectured quark-gluon plasma (QGP) or a high-density hadron gas (HG). The elementary processes involved –$q\overline{q}$ annihilation in the QGP phase and $\pi^+\pi^-$ annihilation in the HG phase– are well known. Yet, the absolute yields, obtained by integrating the emission rate over the space-time evolution of the collision, are theoretically uncertain as the calculations critically depend on the parameters of the time evolution. However, they are expected to have different spectral shapes. In the HG phase, the ρ meson plays a major role; the $\pi^+\pi^-$ annihilation cross section is dominated by the ρ pole in the pion form factor. This dictates the shape of the HG thermal yield: a strong rise from the threshold at $2m_\pi$ and a broad peak at the ρ mass [28, 29]. Chiral symmetry restoration could leave a fingerprint in this picture since the ρ mass is expected to deacrease as one approaches the chiral restoration [30, 31] enhancing the thermal yield at low-masses below the ρ-meson free mass. On the other hand, the $q\overline{q}$ annihilation produces an essentially exponential spectrum with a slope parameter reflecting the temperature of the system; the threshold, given by $2m_q$, is expected to be negligible. Theoretical calculations have singled out the mass range of 1-3 GeV/c^2 as the most appropriate window to observe the thermal radiation from the QGP phase [28, 32].

The physics potential of dileptons is further emphasized by the ability to measure the vector mesons –which are considered as important messengers of the collision dynamics [33, 34]– through their leptonic decays.

The difficulties

The interest in dileptons is matched by the difficulty of their experimental detection, which explains why first results became available only recently. The main difficulty is the huge *combinatorial background* of pairs from uncorrelated lepton tracks originating from the decay of hadronic particles (and from conversions in the measurements of electron pairs). This background has a quadratic dependence with multiplicity and strongly increases as the coverage moves to the low-mass and low-p_t regions.

Another factor limiting the sensitivity to any new source is set by the uncertainties in the contributions from the known sources, i.e. the *physics background*. At masses m $\leq$ 1 GeV/c^2, the main sources of dileptons in hadron-hadron collisions come from the electromagnetic decay of hadrons, $\pi^o,\eta,\eta' \rightarrow e^+e^-\gamma$; $\omega \rightarrow e^+e^-\pi^o$; $\omega,\rho,\phi \rightarrow e^+e^-$. Most are produced at a late stage of the collision, long after freeze-out. For quite some time there was believed to be an excess of dileptons in this mass region known as "anomalous" dileptons [35]. Recent results on p-Be first reported by HELIOS/1 [36] and later confirmed by CERES [37] (see Fig. 9 below) clearly demonstrate that there is no need to invoke any "anomalous" source within the systematic errors of the order of 50%. In the intermediate mass region (above the ϕ and below the J/ψ) the main known contributions come from the Drell-Yan process and the semi-leptonic decay of the charmed mesons $D\overline{D}$.

Given all these uncertainties and lacking precise theoretical guidelines, the experimetalist's approach has been a systematic one, performing in the same apparatus the best measurements possible of the dilepton production in pp, pA and AA collisions, using the first two as the basis for identifying any possible deviation from the known physics in AA collisions. The results below show evidences of such deviations.

Experimental results

The three experiments measuring lepton pairs, HELIOS/3, NA38 and NA45/CERES have recently reported results on S-induced interactions showing an enhanced production of dileptons – either e^+e^- or $\mu^+\mu^-$ pairs – over a very broad invariant-mass range, from $m_{ll} \sim 200$ MeV/c^2 up to the J/ψ [39]. The enhancement is relative to the known sources as measured in pp or pA collisions after scaling to the S-nucleus case. The effect is beautifully illustrated in Fig. 8 which shows the results of HELIOS/3 in central S-W interactions together with those obtained in p-W at 200 GeV/nucleon [38]. They are presented in

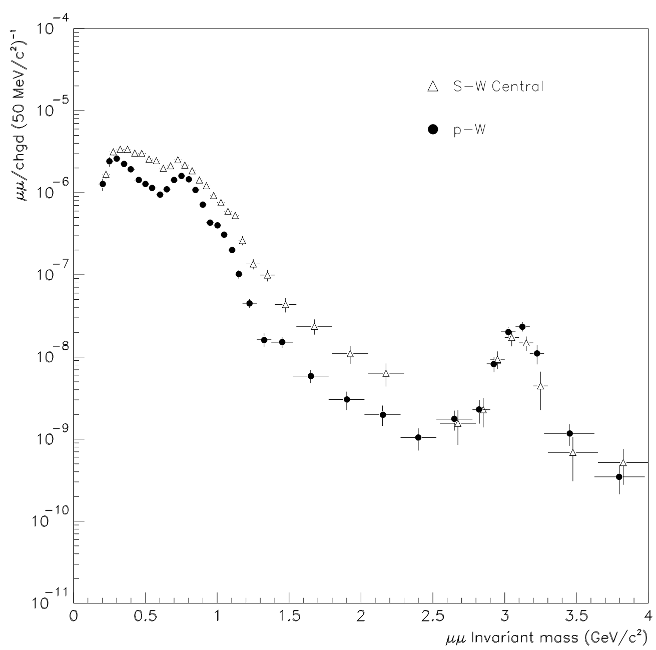

Figure 8: Dimuon invariant mass spectra measured by HELIOS/3 in p-W and in central S-W interactions at 200 GeV/nucleon [38].

the form of muon pairs per charged particle measured in the same rapidity interval. The enhancement covers a very broad mass range including the low-mass continuum (m = 200 - 600 MeV/c^2), the vector mesons ρ, ω and ϕ, and the intermediate-mass continuum (above the ϕ and below the J/ψ masses). The figure also displays the well known J/ψ suppression, a topic of interest in its own right which will be discussed separately (see

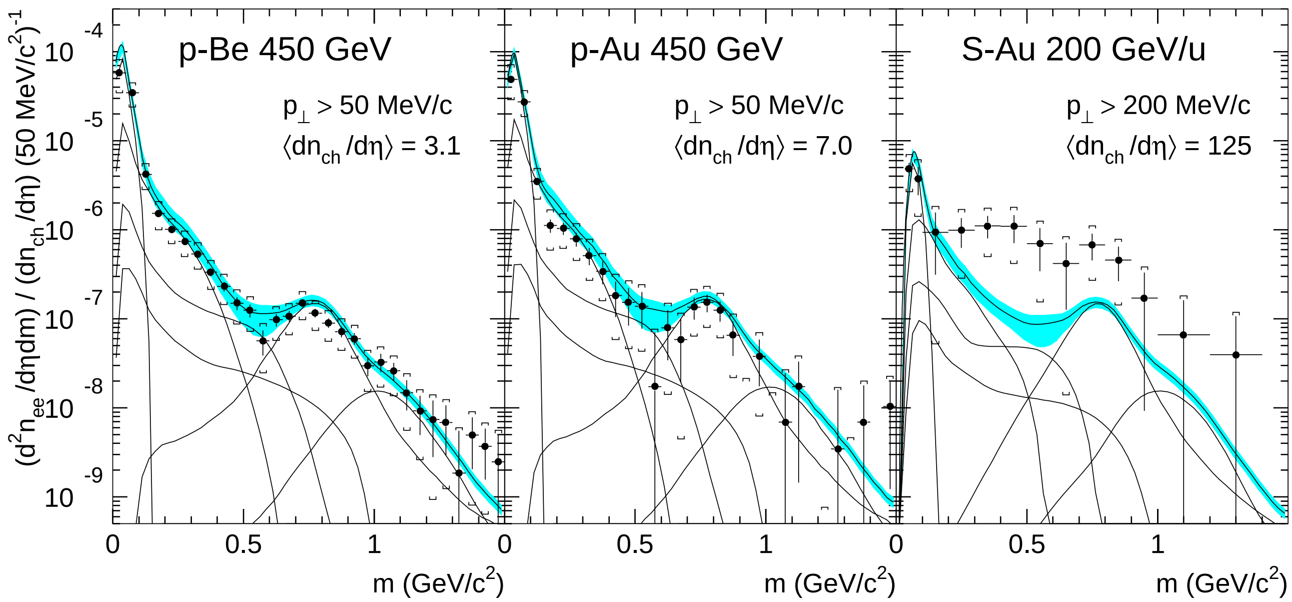

Figure 9: Inclusive e^+e^- mass spectra in 450 GeV p-Be and p-Au collisions, and in 200 GeV/nucleon S-Au collisions measured by CERES. The solid lines represent the contributions from the various known hadron decays; the shaded area indicate the systematic error on the summed contributions. The data are normalized to give the pair density per charged particle density within the acceptance of the CERES spectrometer [37].

Section 5). NA38 has also reported an excess of dimuon pairs in the intermediate mass region, which is consistent with HELIOS/3 [40].

The most dramatic effect is the one observed by the CERES experiment in S-Au collisions as shown in Fig. 9 [37]. The low-mass spectra measured in p-Be (a very good approximation to the p-p system) and p-Au collisions are well reproduced, within systematic errors, by electron pairs from the known hadronic sources. The situation is however very different in the S-Au case. The measured S-Au mass spectrum has a different shape and shows a yield much larger than the one predicted from hadron decays, reaching even one order of magnitude at masses around 0.4 GeV/c^2.

The enhancement factor, quantified by the ratio of the integral of the data over the integral of the predicted sources, is 5.0±0.7(stat.)±2.0(syst.) in the mass range of m = 0.2 – 1.5 GeV/c^2 [37]. The HELIOS/3 enhancement factor in the above mass range is estimated to be ∼1.6, significantly smaller than that of CERES; the discrepancy could be a consequence of the different rapidity coverage of the two experiments, if the dilepton production mechanism has a non-linear (quadratic?) dependence on the event multiplicity. Indeed, CERES covers the mid-rapidity region of η= 2.10 – 2.65, whereas HELIOS/3 covers the forward region η= 3.7 – 5.5. Consequently, the average charged-particle rapidity densities accessible by the two experiments, and hence the energy densities, differ by at least a factor of two [12]. This interpretation is supported by preliminary results of HELIOS/3, showing that there is practically no excess at the most forward rapidities (y > 4.4) covered by the spectrometer, whereas almost all the excess is at lower rapidities

[41].

Another interesting question is whether the excess below and above the vector mesons ρ, ω and ϕ have the same origin. The HELIOS-3 analysis seems to favor a common origin [38]. On the other hand, NA38 suggests an enhanced charm production as a possible explanation of the excess in the intermediate mass range [42]. One would then need a different explanation for the observed enhancement at low masses since charm production has a negligible contribution there. Data on the multiplicity dependence and p_t distribution of the excess may shed light on this issue.

Interpretations

The enhancement of lepton pairs in the continua below and above the vector meson resonances is an outstanding result. It has triggered intensive theoretical activity which is now in full swing to assess its origin. The attention is mainly focussed on the electron data which have been measured at mid-rapidity and are therefore more accessible to calculations using standard hydrodynamical models. A possible explanation comes immediately to mind from the characteristic features of the low-mass dilepton excess [37]: its onset at a mass $m_{\ell\ell} \sim 2m_\pi$, its extension to the low-mass region below and around the ρ-meson, and the possibility of a quadratic dependence with multiplicity suggest that the excess is due to $\pi^+\pi^-$ annihilation into $\ell^+\ell^-$. This would then be the first indication of radiation emitted from the dense hadronic matter formed in relativistic heavy-ion collisions.

This hypothesis alone is not able to account for the excess at low-mass pairs (m = 200 - 500 MeV/c^2) since as noted previously, the cross section is dominated by the pole of the pion form factor at the ρ mass [43]. However, by taking into account the decrease of the ρ mass which has been advocated as a precursor of chiral symmetry resotration, Li, Ko and Brown have shown a remarkable agreement with the CERES data [44]. Since the pions have a thermal distribution the cross section is greatly enhanced by the reduced ρ mass producing a large yield of electron pairs at low invariant masses. Their approach invokes the formation of a hot and dense hadronic matter without requiring a QGP state.

The CERES results have also been analyzed using a standard hydrodynamical scenario invoking formation of a thermalized quark-gluon plasma which evolves through a mixed phase of quark matter and hadrons to a final hadron gas phase [45]. The calculations include electron pairs emitted from the pure QGP phase, the QGP and the HG components of the mixed phase and the pure HG phase. The dominant contribution comes from two-meson annihilation in the hadronic component of the mixed phase. The calculations reproduce the yield in the ρ mass region but underpredicts the yield at low masses.

4 DIRECT PHOTONS

The motivation to search for direct photons is the same as for the measurement of dileptons since real and virtual photons carry the same physics information. Single direct photons are therefore expected to be emitted as thermal radiation by the hot and dense matter formed at the early stages of the collision in analogy to the thermal dileptons.

Two experiments are presently involved in the measurement of direct photons; WA80 which measures them directly and CERES which uses the conversion method, both covering almost the same p_t and mid-rapidity intervals. The inclusive photon

p_t distribution measured by CERES is shown in Figure 10 and is compared to the expectations from hadronic sources [46]. Within errors, there is no evidence for direct photons. The final analysis of the WA80 data reaches the same conclusion [47] and both experiments agree to an upper limit –at the 90% confidence level– of the order of 15% (of the total inclusive photon yield) for the emission of direct photons in central S-Au collisions.

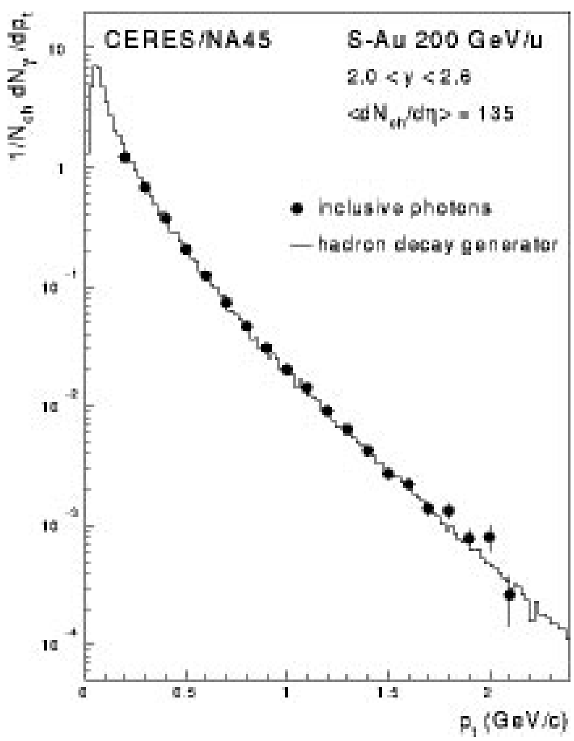

Figure 10: CERES results on inclusive photon p_t distribution from central S-Au collisions and comparison to predictions from hadron decays [46].

The lack of signal in the photon data is striking in view of the strong enhancement of low-mass electron pairs discussed in the previous section. The above mentioned arguments are certainly valid, direct photons should provide analogous information to thermal dileptons. The question is only a quantitative one, namely the level of sensitivity of the two measurements to a new source with respect to their hadronic background. Simple arguments reveal that the level of sensitivity is more than two orders of magnitude lower for photons compared to electrons [39]. In other words, the enhancement factor of 5 observed in the case of electrons should translate into an enhancement factor of a few percent in the photon measurement and this is consistent with the experimental results.

5 CHARMONIUM SUPPRESSION

The suppression of the J/ψ was one of the first predicted signatures of deconfinement [48]. The suppression results from the Debye color screening effect of the plasma: a $c\bar{c}$

formed in the initial hard collisions mainly via gluon fusion $gg \rightarrow c\bar{c}$ does not lead to the formation of a J/ψ bound state if the color screening radius is smaller than the size of the J/ψ. The $c\bar{c}$ quarks separate, appearing later as two open charm mesons. Using the same picture a stronger suppression is predicted for the ψ' which is less bound and has a radius almost twice as large as that of the J/ψ. The suppression was also predicted to decrease with p_t since a fast $c\bar{c}$ may escape the medium before forming the J/ψ.

All these effects have been observed by the NA38 experiment which focusses on the study of charmonium production through its decay into $\mu^+\mu^-$ pairs. NA38 has by now a beautiful set of results on J/ψ and ψ' production in p-A (A= C, Al, Cu, W and U) at 200 and 450 GeV/c, in S-U at 200 GeV/c [49]. The measurements are presently extended to Pb-Pb collisions at 160 GeV/u. A sample of the NA38 results is presented in Fig. 11 which shows the J/ψ suppression as a function of E_t in S-U collisions. The suppression is illustrated relative to the high mass Drell-Yan continuum which is measured in the same experiment and is well understood. The same figure displays the ratio ψ'/ψ as a function of E_t clearly demonstrating that the ψ' resonance is more suppressed than the J/ψ. It is interesting to note that this ratio is found to be surprisingly constant in p-A collisions both as a function of A and of $\sqrt{s}$ with an average value of 1.74%.

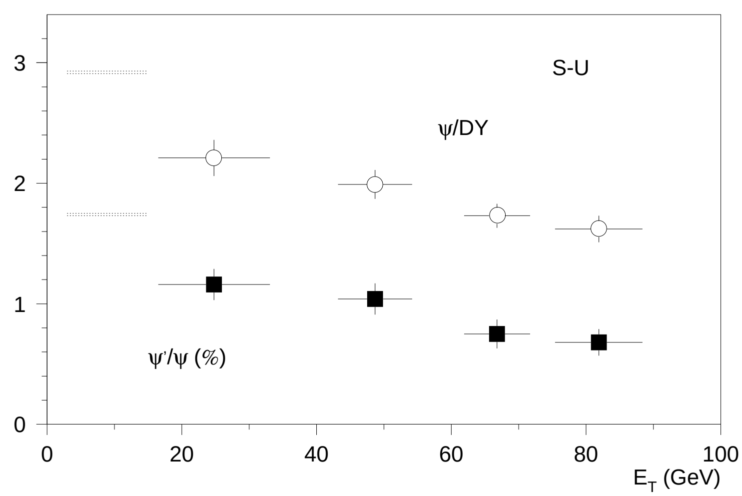

Figure 11: Ratios of ψ/DY and ψ'/ψ in S-U collisions versus centrality(NA38)

The NA38 results, some of which were already reported after the first ion run, almost 9 years ago, initially provided prominent support to the QGP hypothesis. However, this hypothesis was soon contested and considerable efforts were devoted to provide alternative explanations, in particular as the picture became confused by experimental evidence of J/ψ suppression in hadron-nucleus collisions where a QGP scenario cannot be invoked. Taking into account initial state parton scattering effects on the $c\bar{c}$ production allows to reproduce the observed p_t dependence of the suppression [50]. Adding to that the J/ψ absorption in normal nuclear matter with a cross section $\sigma^{abs}_{\psi N}$= 6-7 mb explains the observed suppression both in p-A and A-A collisions [51]. In a recent work Satz and Kharzeev reach the same conclusion but with a different underlying physical picture [52].

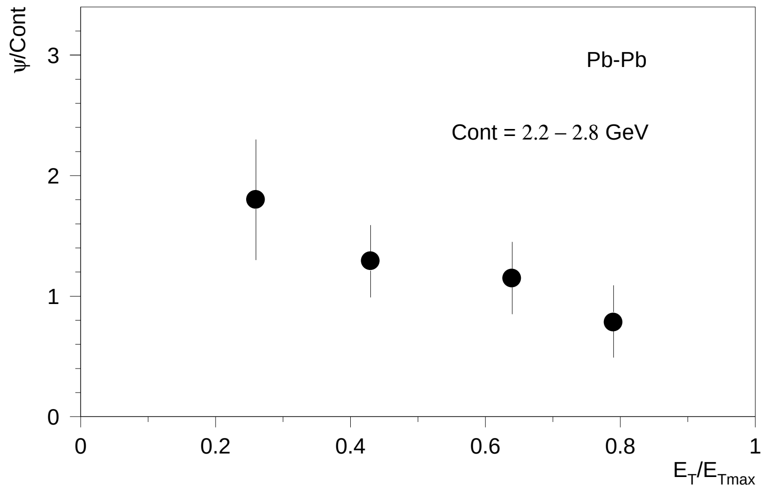

Figure 12: Ratio of $J/\psi/$ over continuum in Pb-Pb collisions versus centrality (NA38)

The J/ψ and ψ' supression in p-A collisions and the J/ψ suppression in A-A collisions are explained by the absorption of the pre-resonance $c\bar{c}g$ state in the nuclear medium. The stronger suppression of the ψ' in A-A collisions is attributed to some additional absorption effects in the hadronic medium as it is more loosely bound.

In conclusion, at present all experimental observations in p-A and A-A are quantitatively accounted for by J/ψ interactions in confined nuclear matter and there is no need to invoke the melting of the resonance in a QGP. J/ψ suppression remains nevertheless an important issue. The measurements are being extended to Pb-Pb collisions; preliminary results are in qualitative agreement with the S results (see Fig.12) and a quantitative evaluation is awaited to assess whether the additional suppression effects expected from deconfinement become visible in the more favorable conditions offered by the Pb beam.

6 SUMMARY AND OUTLOOK

The light-ion phase, now completed as far as data taking is concerned and almost completed as far as analysis goes, has yielded a tremendous amount of results. The following picture seems to emerge: a high density state is formed in central collisions with energy densities close or slightly above those predicted for the transition into a QGP state. There is growing evidence that the system is in thermal and chemical equilibrium at the time of freeze-out and that it underwent radial expansion. However the answer to the basic question, what is the nature of the system in its early stages remains elusive. The by now classical effects of strangeness enhancement and J/ψ suppression, which have been widely advocated as signatures of the phase transition, seem to be explained in terms of conventional processes and there is no compelling reason to invoke any new phenomena. The recent results on the enhancement of lepton pairs have created considerable excitement; however some caution is needed at this stage at which the amount and quality of the data are limited.

The experimental programme is now engaged in a new phase of really heavy ions, with the Au beam at the AGS and the Pb beam at the SPS. This results mainly in larger volumes and consequently larger lifetimes and slightly higher energy densities. The preliminary results already available from hadronic observables confirm and consolidate the insight gained with light ions. This trend is expected to continue as more results appear. One can also hope that this round of experiments will help to elucidate the nature of the primordial state as the expected signatures of the phase transition might become visible under the better conditions offered by the heavier ions. In particular, results on lepton pairs including not only invariant mass spectra but also multiplicity and p_t distributions, are eagerly awaited. Finally, the Pb beam at CERN will provide the unique opportunity to perform a physics analysis on an event-by-event basis, bringing an entire new dimension to this field of research.

Looking forward in time, the program will be extended to much higher energies when the RHIC at BNL starts operation at the end of the century, colliding Au on Au at a cm energy of 200 GeV/u. Two large detectors, PHENIX and STAR and some smaller ones, are under construction. Even higher energies are expected in a somewhat more distant future at the LHC at CERN with Pb-Pb collisions at $\sqrt{s} = 5.5$ TeV/u. Here ALICE, a dedicated detector for heavy ion physics, is being designed. Compared to the present fixed target experiments, the future colliders will bring a considerable increase in volume, lifetime and energy densities. A new regime will also open up. The fixed target experiments are characterized by a sizable amount of nuclear stopping, resulting in a baryon-rich system. With the energies foreseen at RHIC and even more at LHC, transparency is expected to dominate leading to a baryon-free system in the central rapidity region. Only then we will be creating in the laboratory a system at the conditions which presumably prevailed in the early universe.

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References

[1] T.D. Lee and G.C. Wick, Phys. Rev. D9 (1974) 2991.

[2] For a review see e.g. Proc. of Lattice '94 Nucl. Phys. (Proc. Suppl.) 42 (1995).

[3] See e.g. the Proc. of the last Quark Matter Conf. Nucl. Phys. A566 (1994) and A590 (1995).

[4] F. Antinori et al., Nucl. Phys. A590 (1995) 139c.

[5] E. Gatti and P. Rehak, Nucl. Instrum. Methods A225 (1984) 608; U. Faschingbauer et al., Nucl. Instrum. Methods (in press).

[6] R. Baur et al., Nucl. Instrum. Methods Phys. Res. A343 (1994) 87.

[7] M. Fuchs, Nucl. Instrum. Methods (in press).

[8] R. Stock, Proc. INPC, Beijing, Aug. 21-26, 1995.

[9] T. Alber etal., Phys. Rev. Lett. 75 (1995) 3814.

[10] K. Werner, Phys. Rep. 232 (1993) 87.

[11] B. Andersson et al., Nucl. Phys B281 (1995) 286.

[12] T. Akesson et al., Nucl. Phys. B353 (1991) 1.

[13] D. Bjorken, Phys. Rev. D27 (1983) 140.

[14] J. Cleymans and H. Satz, Z. Physik C57 (1993) 135.

[15] P. Braun-Munzinger, J. Stachel, J.P. Wessels and N. Xu, Phys. Lett. B344 (1995) 43 and in print.

[16] T. Abbot et al., Nucl. Phys. A544 (1992) 237.

[17] J.Rafelski, Phys. Rep. 88 (1982) 331.

[18] see e.g. Proc. Workshop on Strangeness in Hadronic Matter, Tucson, January 4-6, 1995.

[19] D. Di Bari et al., Nucl. Phys. A590 (1995) 307c and J.B. Kinson et al., Nucl. Phys. A590 (1995) 317c.

[20] R. Hagedorn, Suppl. Nuovo Cimento 3 (1965) 147.

[21] E. Schnedermann et al., Phys. Rev. C48 (1993) 2462.

[22] J. Barrette et al, Phys. Rev. Lett. 73 (1994) 2532.

[23] R. Hanbury-Brown and R.Q. Twiss, Nature 178 (1956) 1046.

[24] B. Jacak, Nucl. Phys. A590 (1995) 215.

[25] H. Sorge, H. Stoecker and W. Greiner, Ann. Phys. 192 (1989) 266.

[26] H. Beker et al., Phys. Rev. Lett. 74 (1995) 3340.

[27] E.V. Shuryak, Phys. Lett. B78 (1978) 150.

[28] K. Kajantie, et al., Phys. Rev. D34 (1986) 2746.

[29] J. Cleymans, K. Redlich and H. Satz, Z. Phys. C52 (1991) 517.

[30] R. Pisarski, Phys. Lett. B110 (1982) 155.

[31] G.E. Brown and M. Rho, Phys. Rev. Lett. 66 (1991) 2720.

[32] P.V. Ruuskanen, Nucl. Phys. A544 (1992) 169c.

[33] A. Shor, Phys. Rev. Lett. 54, 1122 (1985).

[34] U. Heinz and K.S. Lee, Phys. Lett. B259, 162 (1991).

[35] T. Akesson et. al., Phys. Lett. 152B (1985) 411 and 192B (1987) 463.

[36] T. Akesson et. al., Z. Phys. C68 (1995) 47.

[37] G. Agakichiev et al., Phys. Rev. Lett. 75 (1995) 1272.

[38] M. Masera, Nucl. Phys. A590 (1995) 93c.

[39] for a recent review see I. Tserruya, Nucl. Phys. A590 (1995) 127c and Proc. XXX Rencontres de Moriond on "QCD and High Energy Hadronic interactions" Les Arcs 19-26 March, 1995.

[40] M. C. Abreu et al, Nucl. Phys. A566 (1994) 77c.

[41] G. London, Proceedings of the Workshop on Dilepton Production In Relativistic Heavy ion Collisions, March 2-4, 1994, GSI, Darmstadt, Germany.

[42] C. Lourenco, Proc. of the 5th Conf. on Intersections between Particle and Nulear Physics, St. Petersburg, FL (1994).

[43] W. Cassing, W. Ehehalt and C.M. Ko Phys. Lett. B363 (1995) 35.

[44] G.Q. Li, C.M. Ko and G. Brown, submitted to Phys. Rev. Lett.

[45] D.K. Srivastava, B. Sinha and C. Gale, Phys. Rev. (in press).

[46] P. Wurm et al., Nucl. Phys. A590 (1995) 103c.

[47] R. Albrecht et al., Preprint

[48] T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416.

[49] see e.g. S. Ramos et al., Nucl. Phys. A590 (1995) 117c and ref. therein.

[50] J. Hufner, K. Kurihara and H.J. Pirner, Phys. Lett. B215 (1988) 218.

[51] C. Gerschel and J. Hufner, Z. Physik C56 (1992) 171.

[52] D. Kharzeev and H. Satz, preprint CERN-TH/95-214r.